

Final Technical Report

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Participation in the Cluster Magnetometer Consortium for the Cluster Mission 067142**Grant: NAG5-1167****Project Period: 7/15/1989 - 6/30/1997****Margaret Kivelson, P.I.*****Introduction***

Prof. M. G. Kivelson (UCLA) and Dr. R. C. Elphic (LANL) are Co-investigators on the Cluster Magnetometer Consortium (CMC) that provided the fluxgate magnetometers and associated mission support for the Cluster Mission. The CMC designated UCLA as the site with primary responsibility for the inter-calibration of data from the four spacecraft and the production of fully corrected data critical to achieving the mission objectives. UCLA was also charged with distributing magnetometer data to the U.S. Co-investigators. UCLA also supported the Technical Management Team, which was responsible for the detailed design of the instrument and its interface.

In this final progress report we detail the progress made by the UCLA team in achieving the mission objectives.

Calibration

One of the main objectives of the Cluster Mission was to measure the spatial gradients of the magnetic field in the Earth's magnetosphere. As gradients require the knowledge of first order differences, small errors resulting from an inadequate knowledge of the orientations, zero levels and the scale factors of the magnetometer sensors significantly affect the calculation of field gradients and must be removed with high accuracy. We showed that twelve calibration parameters are required for each of the four spacecraft to correctly infer the measured magnetic fields at each of the spacecraft. We developed a procedure for the complete calibration of the spacecraft tetrad as a two step process. As the first step we developed a technique called intra-calibration, which makes use of the fact that low frequency geophysical signals in the Earth's magnetosphere have a broad band character. This method provides eight of the required twelve calibration parameters for each of the four magnetometers. As a second stage we developed a technique called inter-calibration which determines the remaining calibration parameters by using the concept that $\nabla \cdot \mathbf{B}$ is zero everywhere and $\nabla \times \mathbf{B}$ is vanishingly small in certain regions of the magnetosphere.

The calibration work has been fully archived in the three publications listed below and several internal IGPP documents and memos.

Intra-calibration

Most of the existing calibration schemes are not sufficiently automated to handle the large amount of calibration required for a Cluster type mission. Our highly automated calibration scheme exploits the fact that errors in eight of the twelve calibration parameters generate coherent monochromatic signals at the first and the second harmonics of the spin frequency in the despun data. These narrow-band signals can be readily characterized because of the natural constraint that low frequency geophysical signals in the Earth's magnetosphere have a broad band character. We related the real and the imaginary parts of the monochromatic signals to the eight calibration parameters. The least squares scheme improves the eight calibration parameters by iteration until the power of the coherent signal is minimized. The scheme was

extensively tested on ISEE and Galileo data sets and the results were extremely satisfactory. The technique is described in detail in *Kepko et al.*, [1996].

Inter-calibration

The inter-calibration technique relies on the concept that $\nabla \cdot \mathbf{B}$ is zero everywhere in space and the electric current, $\nabla \times \mathbf{B}$, is vanishingly small in certain regions of the magnetosphere. If the data have not been properly intercalibrated, they yield non-zero averages for $\nabla \cdot \mathbf{B}$ and $\nabla \times \mathbf{B}$ in those regions. Correct calibration parameters are determined by requiring that the final data set must yield values of $\nabla \cdot \mathbf{B}$ and $\nabla \times \mathbf{B}$ close to zero.

The approach uses an error propagation scheme for determining the calibration parameters. Miscalibrated magnetic field data introduce errors into the nine first order gradients. By using Taylor series expansions of the measurements around a point enclosed by the tetrad one can analytically propagate errors from the individual field values into the first derivative terms. The errors from these gradients are then analytically propagated into $\nabla \cdot \mathbf{B}$ and $\nabla \times \mathbf{B}$. This error is called the analytic error in $\nabla \cdot \mathbf{B}$ and $\nabla \times \mathbf{B}$. By inverting the uncorrected data collected by the tetrad in current-free regions, one can estimate the errors in the measured $\nabla \times \mathbf{B}$ and $\nabla \cdot \mathbf{B}$ terms. We minimized the difference between the analytical and the measured errors in $\nabla \cdot \mathbf{B}$ and $\nabla \times \mathbf{B}$. The condition for minimization gives the correct calibration parameters in terms of the input data. The technique is extremely efficient, provided appropriate input data are available, and should prove extremely useful for the new Cluster mission. The details of the technique were reported in *Khurana et al.* [1996].

Scientific Analysis Tools

Cluster Data Analysis Tool (CDAT)

In order to display and study simultaneous data from several spacecraft, new innovative software is required. We developed software (named CDAT) on a Macintosh computer that sets a new standard for efficient display and analysis of long time series. The boundary and wave analysis tools are incorporated within CDAT. It also performs minimum variance analysis on the vector field data. The software was subsequently ported to Windows-based computers.

The Boundaries Explorer

We developed a boundary analysis tool that uses the "time of crossing" information from the four spacecraft to obtain the orientation and the velocity of planar boundaries. By using additional information about the boundary normals from the magnetic field data (obtained from the minimum variance analysis of vector magnetic field), the tool can also be used to determine the shape of a second order surface.

Wave Analysis Tool

We developed a Fourier transform based wave analysis tool that can be used to obtain the wavelength and phase velocity of plane propagating waves. The tool would be most useful in the sheath region where it can be assumed that the waves are plane propagating waves. The technique relies on the relation between the wave number and phase of the wave and the phases of the Fourier-transformed data measured at the four spacecraft.

Routine Computation of Electric Current Density and $\nabla \cdot \mathbf{B}$

We developed a program to compute the nine spatial gradients of the magnetic field automatically from the fully calibrated data obtained from the four spacecraft. The program also outputs the instantaneous value of the electric current density (\mathbf{J}) and $\nabla \cdot \mathbf{B}$ in the volume enclosed by the tetrad. A data quality indicator, which characterizes the relative spacing between the four spacecraft and the computed value of $\nabla \cdot \mathbf{B}$, is also generated.

Data Management, Processing and Delivery Tools

Data Management

Quick retrieval of a specific data set requires that the data files be organized in a way that is both intuitive to the user and easily understood by the computer operating systems and the database programs. To achieve this goal, the naming convention for the data files and the directories was made compatible with the Planetary Data System (PDS) naming convention developed at UCLA and familiar to others through its extensive use within the space science community. The data retrieval and archiving is accomplished through the UCLA DITDOS and DAISIE database management tools developed in support of the Planetary Data Systems.

The Data Flow System (DFS)

In order to process and calibrate a very large data set an efficient data processing tool is required. For this purpose we adopted a set of Unix based programs called Data Flow System (DFS) developed at the IGPP which use the concept of Unix pipelining. The DFS operates in a SUN/Unix environment. It was installed at Los Alamos National Laboratories (LANL) and at the Technical University, Braunschweig (TUB), which independently developed some calibration routines to provide a useful element of redundancy in this key activity. Because of the modularized approach to processing, new fittings developed at either UCLA or TUB can be easily exchanged or updated, and tested. Software configuration control is readily maintained. Because of the maturity of the DFS and its ongoing development as a basic research tool at UCLA, in-kind software support is effectively available. The FGM software development will benefit from ongoing parallel efforts supporting other projects. DFS tools can be modified to comply with standards and products requirements of the CSDS Working Group.

New Data Processing Modules

Several special purpose modules were written to unpack, format, clean, orthogonalize, despin and rotate (into several geophysical coordinates) the Cluster data set. All of these modules work in the DFS environment and are capable of producing fully calibrated data set from the ESA standard telemetry packets.

Data Distribution

Early in the life of the Mission, it was recognized by both ESA and NASA associated scientists that the common medium to exchange large amount of data between the project, the PIs, and the Co-Is should be write-once CD-ROMS. A CD-ROM can hold 550 Mbytes of data and is cost-effective compared to other media available at the present time. A scheme was developed in which the Experimental Data Records (EDRs) are unbundled; the magnetic data is stripped and written to CD-ROMS for our use and the use of US Co-I teams. The data retrieval and archiving was accomplished through the UCLA DITDOS and DAISIE database management tools developed in support of the Planetary Data Systems. DITDOS and its graphical user interface DAISIE allow the user to access, browse through, visualize, and order any type of data efficiently. The storage media can be hard discs, CD-ROMs or even the magnetic tapes. The data can also be directly introduced into the UCLA data flow system for further processing.

References and other publications supported by our Cluster Grant:

- [Balogh, A. et al., The magnetic field investigation on Cluster, ESA, Publication SP-1103, 1988]
- Kepko, E. L., K. K. Khurana, M. G. Kivelson, R. C. Elphic and C. T. Russell, Accurate determination of magnetic field gradients from four point vector measurements: 1. Use of natural constraints on vector data obtained from a single spinning spacecraft, *IEEE Trans. Magnetics*, 32, pp. 377-385, 1996
- Khurana, K. K., E. L. Kepko, M. G. Kivelson, and R. C. Elphic, Accurate determination of magnetic field gradients from four point vector measurements: 2. Use of natural constraints on vector data obtained from four spinning spacecraft, *IEEE Trans. Magnetics*, 32, 5193, 1996.
- Khurana K. K., E. L. Kepko, and M. G. Kivelson, Measuring magnetic field gradients from four point vector measurements in space, To appear in: AGU monograph on *Measurement Techniques for Space Plasmas*, 1998.

Abstracts of talks supported by our Cluster Grant

- Balogh, A., et al., The magnetic field investigation on Cluster., in *European Space Agency (ESA)*, pp. 15, 1988.
- Kepko, E.L., K.K. Khurana, and M.G. Kivelson, Use of Four Spacecraft in Determining the Characteristics of Boundaries and Surfaces, *EOS, Trans. AGU*, 76, F512, 1996a.
- Kepko, E.L., K.K. Khurana, and M.G. Kivelson, Use of four spacecraft in determining the characteristics of magnetospheric boundaries and phenomena, in *COSPAR*, pp. 184, 1996b.
- Khurana, K.K., and M.G. Kivelson, Measuring Magnetic Field Gradients from Four Point Vector Measurements in Space, in *1995 Chapman Conference*, Santa Fe, 1995.
- Khurana, K.K., E.L. Kepko, and M.G. Kivelson, Use of Empirical Models in Devising Techniques to Calculate Magnetic Gradients Accurately From Four Point Measurements, in *Programme and Abstracts, IUGG XXI General Assembly*, pp. B191, Boulder, Colorado, 1995.